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A review of energy storage technologies for wind power applications

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ABSTRACT

Due to the stochastic nature of wind, electric power generated by wind turbines is highly erratic and may affect both the power quality and the planning of power systems. Energy Storage Systems (ESSs) may play an important role in wind power applications by controlling wind power plant output and providing ancillary services to the power system and therefore, enabling an increased penetration of wind power in the system. This article deals with the review of several energy storage technologies for wind power applications. The main objectives of the article are the introduction of the operating principles, as well as the presentation of the main characteristics of energy storage technologies suitable for stationary applications, and the definition and discussion of potential ESS applications in wind power, according to an extensive literature review.

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Nomenclature

Abbreviations

BESS Battery Energy Storage System
C-PCS Control and Power Conditioning System
CAES Compressed Air Energy Storage
DoD depth of discharge
FBESS Flow Battery Energy Storage System
FESS Flywheel Energy Storage System
HESS Hydrogen-based Energy Storage System
Li-ion lithium-ion
LVRT low voltage ride through
NaS sodium–sulphur
Ni–Cd nickel–cadmium
PHS pumped hydro storage
PSB polysulphide–bromide flow battery
RFC regenerative fuel cell
SCESS supercapacitor energy storage system
SMES superconducting magnetic energy storage
VRB vanadium redox battery
ZBB zinc–bromine flow battery

1. Introduction

Wind energy is one of the fastest growing sources of electricity nowadays. In fact, the cumulative wind power installation in the EU at the end of 2010 was 84,074 MW. Thus, 5.3% of European electricity consumption in 2010 came from wind turbines. The penetration of wind power in some European countries has reached values around 20%, as in the case of Denmark (24%) [1]. Electric power, generated by wind turbines, is highly erratic, and therefore the wind power penetration in power systems can lead to problems related system operation and the planning of power systems [2]. These problems may be especially important in islanded grids.

Therefore, wind generation facilities are required, in accordance with grid codes, to present special control capabilities with output power and voltage, to withstand disturbances and short circuits in the network during defined periods of time [3]. In this way, wind farms are known as wind power plants.

In this scenario, ESS play an important role in wind power applications by controlling wind power plant output and providing ancillary services to the power system and thus, enabling an increased penetration of wind power in the system.

Numerous publications regarding the review of suitable storage technologies for stationary applications are found in literature [4–6]. In [5,6], a summary of ESS main features is provided. In addition, a revision of specific, worldwide ESS examples for renewable energy applications is detailed in [4].

Accordingly, this article focuses on two main objectives; firstly, the introduction of operating principles and the main characteristics of several storage technologies suitable for stationary applications; and, secondly, the definition and discussion of potential ESS applications in wind power. The classification of potential ESS applications has been performed under full power duration of the storage criteria in each case. Thus, applications where ESS are required to inject or absorb power for less than a minute, as in power smoothing of wind turbines; or long-term storage applications, such as those related to load following or seasonal storage, have been considered.

2. Energy storage technologies

Electrical energy can be converted to many different forms for storage [6]:

- as gravitational potential energy with water reservoirs,
- as compressed air,
- as electrochemical energy in batteries and flow batteries,
- as chemical energy in fuel cells,
- as kinetic energy in flywheels,
- as magnetic field in inductors,
- as electric field in capacitors.

In this section, a review of several available technologies of energy storage that can be used for wind power applications is evaluated. Among other aspects, the operating principles, the main components and the most relevant characteristics of each technology are detailed. In order to obtain an overview of the main characteristics of the energy storage technologies presented in this work, and the differences between them in a comprehensive way, some tables (see Tables 1 and 2) and graphics (see Figs. 7 and 8), based on the data collected from several publications and manufacturers, are shown.

2.1. Pumped hydro storage (PHS)

PHS is a large scale energy storage system. Its operating principle is based on managing the gravitational potential energy of water, by pumping it from a lower reservoir to an upper reservoir during periods of low power demand. When the power demand is high, water flows from the upper reservoir to the lower reservoir, activating the turbines to generate electricity. The energy stored is proportional to the water volume in the upper reservoir and the height of the waterfall. According to [90], the use of PHS can be divided into 24 h time-scale applications, and applications involving a more prolonged energy storage in time, including several days. Actually, there is a tremendous potential for hydro-storage capacity in many areas globally. In type-one applications, the potential is around 1675 GW, and for type-two, 1454 GW. This technology is the most used for high-power applications [5].

An illustrative example of a PHS installation, is in operation by First Hydro Company [54]. This installation was commissioned in 1984. It can inject 1728 MW for 5 h, including high power ramp rates. The system is capable of moving from 0 to 1320 MW power injection in 12 s by means of managing 6 motor-generators of

Table 1
Characteristics parameters of ESS.

Technology	Capital cost	Energy rating (MW h)	Power rating (MW)	Specific energy (W h/kg)	Specific power (W/kg)
PHS	10–20 €/kW h [7], 35–70 €/kW h [8]	500–8000 [9]	10–1000 [9]	–	–
HESS	2–15 €/kW h [7]	120 [5]	0.1–15 [5], 0.3–50 [10]	100-150 [11], 400–1000 [11]	–
CAES	3–5 €/kW h [7], 10–70 €/kW h [8]	2860 [12], 580 [12]	110 [12], 290 [12], 50–300 [13]	3.2–5.5 [13]	–
VRB	600 $/kW h [14]	2 [15], 6 [16], 1.2–60 [17], 120 [18]	0.25 [15], 6 [16], 0.2-10 [17], 12 [18]	20 [19], 25–35 [20]	166 [21]
ZBB	500 $/kW h [22]	0.1–3 [23], 0.15 [24], 0.4 [25], 2 [26], 2.8 [16], 4 [4]	0.1-1 [23], 0.1 [24], 0.2 [25], 2 [26], 0.5 [16], 1 [4]	60 [27], 70–90 [11], 75–85 [28]	45 [29]
PSB	125–150 €/kW h [7], 450$/kW [14], 360–1000 €/kW h [30]	0.005–120 [20]	0.1–15 [20]	–	–
NaS	210–250 €/kW h [7], 450$/kW h [22]	0.4 [31], 0.4–244.8 [32]	0.05 [31], 0.05–34 [32]	100 [27], 175 [33]	115 [29], 90–230 [34]
Lead-Acid	50–100$/kW h [13], 210–270 €/kW h [7], 185 €/kW h [15]	0.001–40 [15]	0.05–10 [15]	30 [13], 35–50 [35]	180 [13], 200 [29]
Ni–Cd	400–2400$/kW h [13]	6.75 [16]	45 [16]	30–40 [36], 50 [13,27], 45–80 [35]	100–150 [36], 160 [29]
Li-ion	900–1300$/kW h [13]	0.0016 [37], 0.5 [38], 0.0015–50 [39]	0.1 [37], 2 [38], 0.015–50 [39]	80–150 [13], 100–150 [27], 160 [35], 120–200 [40]	245–430 [36], 400-500 [33], 500–2000 [13]
SMES	–	0.001 [41], 0.00083 [4], 0.015 [42]	1 [41], 3 [4], 100 [42], 1–10 [28,43]	10–75 [43]	–
FESS	400–800$/kW h [13]	0.0052 [44], 0.025–5 [45]	1.65 [44], 0.1–20 [45]	20 [11], 5–80 [46], 5–100 [13]	11,900 [47]
SCESS	20,000 $/kW h [13], 6800 €/kW h [48]	0.01 [49]	0.05–0.1 [5], 0.25 [49]	2–5 [40], 5.69 [50], 1–10 [51], 10 [46], 5–15 [5], 30 [52]	800–2000 [5], 2000–5000 [40], 10,000 [13,51], 13800 [50], 23,600 [53]

330 MW activated by reversible Francis water turbines, installed in Europe's largest man-made cavern.

In general, the life time of PHS installations is around 30–50 years, with an acceptable round trip efficiency of 65–75% and power capital costs of 500–1500 €/kW and 10–20 €/kW h [7]. Despite the large power volumes and energy management in PHS installations, it is remarkable that a fast response time (less than 1 min [54]) enables the PHS systems as important components to control electrical network frequency and in provision of reserve generation.

2.2. Compressed Air Energy Storage (CAES)

CAES systems are based on conventional gas turbine technology. In this type of system, the energy is stored in form of compressed air

Table 2
Additional characteristics parameters of ESS.

Technology	Cycling capability	Life (years)	Energy efficiency (%)	Daily self-discharge (%)	Manufacturers
PHS	2×10^4–5×10^4 [23]	30–50 [7], 50 [9]	65–75 [7], 67 [9], 75–80 [13,19]	No [9]	First Hydro Company [54], MWH [55]
HESS	2×10^4 [11]	15 [11]	35 [5], 40 [56], 35–40 [57], 42 [58]	No [10]	Fuel Cell Energy Inc. [10]
CAES	10^4 to 3×10^4 [23]	30 [56], 40 [19]	70 [5], 71 [19], 73 [13]	No [9]	Enis Windgen [59], Dresser-Rand [60]
VRB	1000 [27], 13000 [61]	10 [17], 15–20 [62], 20 [19,20]	65–75 [17], 76 [19], 75–85 [28], 78 [61], 72-88 [63]	Very low [17]	Prudent Energy Corp. [17]
ZBB	2000 [64], 2500 [61]	8–10 [62]	65–75 [49], 68 [61], 70 [65], 80 [20], 75–85 [28]	No [66]	Redflow [66], ZBB Energy Corp. [67], Premium Power Corp. [24]
PSB	–	15 [20]	60–65 [62], 75 [20]	No [20]	Regenesys Technologies [68]
NaS	2500 [31]	12–20 [9], 10–15 [7]	75–85 [7], 80 [69], 85 [9], 84–87 [13]	No [31]	NGK [70]
Lead-Acid	200–300 [30], 500 [71], 1200–1800 [13], 1800 [63]	5–15 [13]	75–80 [7], 70–80 [63]	<0.1 [13], 0.1 [72,6], 0.2 [65]	Alcad [73], Exide Technologies [74]
Ni–Cd	3500 [15][69]	13–16 [62], 20 [35,69]	72 [75]	0.2 [72], 0.3 [13]	Saft [39], Alcad [73], Harding Energy Inc. [36]
Li-ion	1500 [13], 3500 [76]	14–16 [62]	78 [76], 88 [37]	1 [6], 5 [13]	A123 Systems [38], Li-Tec Battery GmbH. [77], Harding Energy Inc. [36]
SMES	10^4–10^5 [78]	20 [29]	80 [6], 90 [78], 95 [79]	10–15 [4]	Superconductor Technologies Inc. [80], American Superconductor Corp. [81]
FESS	10^5–10^7 [13]	20 [45]	85 [5]	100 [13]	Beacon Power [45], Active Power [82], Piller [44]
SCESS	5×10^5 [13], 10^6 [51]	8–10 [5], 12 [13], 17 [83]	65 [65], 80 [6,84], 90 [85,86]	5 [5], 10–20 [6]	Maxwell [83], EPCOS [87], ESMA [88], NEC-Tokin [89]

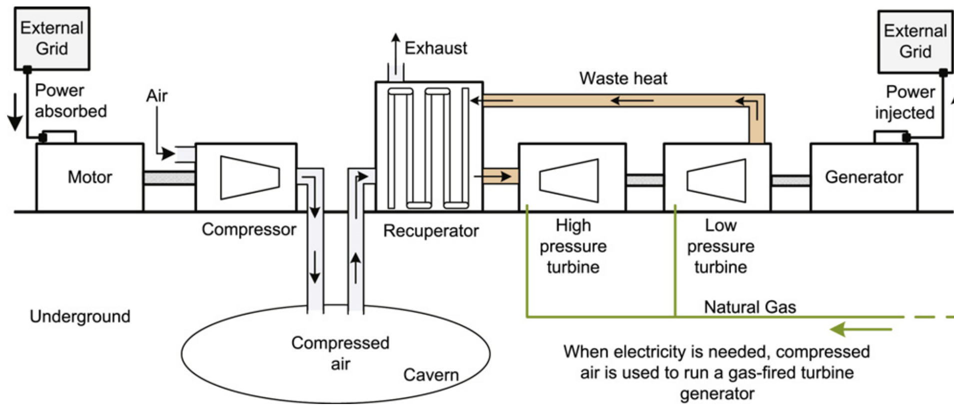

Fig. 1. System description of Compressed Air Energy Storage.

in an underground storage cavern. When energy is required to be injected into the grid, the compressed air is drawn from the storage cavern, heated and then expanded in a set of high and low pressure turbines which convert most of the energy of the compressed air into rotational kinetic energy. The air is additionally mixed with natural gas and combusted. While the turbines are connected to electrical generators in order to obtain electrical energy, the turbine exhaust is used to heat the cavern air. The topology of the whole system is shown in Fig. 1.

Currently, the use of CAES systems is not widespread. Only two plants have been constructed in the world so far; one in Germany (290 MW) and the other in the USA (110 MW) [5]. Nevertheless, this technology is currently attracting much interest. One of the biggest projects that is being carried out is the Iowa Stored Energy Park, with 2700 MW of turbine power. This is being developed in conjunction with a large wind farm. The aim of CAES is to store the excess of wind energy generation [91].

Advances in this technology have led to the development of Advanced-Adiabatic CAES (AA-CAES). As its name suggests, the air is adiabatically compressed and then pumped into an underground cavern. The key parts of this system are the heat exchangers, which are quite expensive. The effectiveness and the economics of these heat exchangers, and the compressor and expander trains are the main concerns for the success of AA-CAES [6].

The life time of CAES installations is approximately 40 years, with an energy efficiency of 71% [19]. Since the self-discharge of the system is very low, CAES systems are considered long-term time scale storage installations which can compete with PHS.

2.3. Battery Energy Storage System (BESS)

Batteries are one of the most used energy storage technologies available on the market. The energy is stored in the form of electrochemical energy, in a set of multiple cells, connected in series or in parallel or both, in order to obtain the desired voltage and capacity. Each cell consists of two conductor electrodes and an electrolyte, placed together in a special, sealed container and connected to an external source or load [92]. The electrolyte enables the exchange of ions between the two electrodes; while the electrons flow through the external circuit. BESS is a solution based on low-voltage power battery modules, connected in series / parallel in order to achieve the desired electrical characteristics. According to [30], BESS comprises batteries, the Control and Power Conditioning System (C-PCS) and the rest of the plant, which is in charge of providing good protection for the entire system (see Fig. 2).

Many types of batteries are now mature technologies. In fact, research activities involving Lead-Acid batteries have been conducted for over 140 years. Notwithstanding, a tremendous effort is being carried out to turn technologies like nickel–cadmium and lithium-ion batteries into cost effective options for higher power applications. In the following sections, a description of some of the most important typologies of batteries is presented.

2.3.1. Lead-Acid battery

The Lead-Acid battery is the most mature type of battery. It is made up of stacked cells, immersed in a dilute solution of sulfuric acid (H_2SO_4) as an electrolyte. The positive electrode of each cell is composed of lead dioxide (PbO_2), while the negative electrode is sponge lead (Pb). During discharge, both electrodes are converted into lead sulphate ($PbSO_4$). During the charge cycle, both electrodes return to their initial state. There are two major types of Lead-Acid batteries: flooded batteries, which is the most common topology, and valve-regulated batteries, which are the subject of extensive research and development [93,233].

The reversible redox reactions deteriorate the battery electrodes, giving them a cycle life of 1200–1800 cycles (depending on the depth of discharge, DoD), with a round trip efficiency of 75–80%. The life time of the system is approximately 5–15 years [94] and depends on the operating temperature of the system. In fact, high operating temperatures (up to 45 °C [13]) can improve the battery performance in terms of higher capacity, but reduce the life time of the system. Due to their low daily self-discharge, <0.1% [94], Lead-Acid batteries are suitable for storing energy for long periods of time [95].

In addition to the relatively poor performance of the battery at low and high ambient temperatures, and its relatively short life time, the main disadvantages of the Lead-Acid battery are the necessity for periodic water maintenance (in the case of a flooded

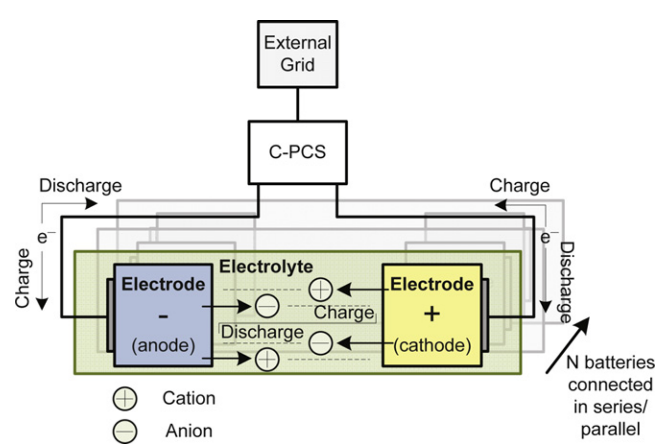

Fig. 2. Operation principle of Battery Energy Storage System.

battery) and its low specific energy and power, 30 W h/kg and 180 W/kg respectively. In addition, Lead-Acid batteries present difficulties in providing frequent power cycling, often at a partial state of charge, which can lead to premature failure due to sulphation [15].

2.3.2. Nickel–cadmium battery (Ni–Cd)

Development of this type of alkaline rechargeable batteries has been carried out since 1950. This has helped to make them a well-established technology in the market place. The main components of Ni–Cd batteries are nickel species and cadmium species as the positive and negative electrodes' active materials respectively, and aqueous alkali solution as the electrolyte [96]. During the discharge cycle, $Ni(OH)_2$ is the active material of the positive electrode, and $Cd(OH)_2$ is the active material of the negative electrode. During the charge cycle, NiOOH is the active material of the positive electrode, and metallic Cd the active material of the negative electrode. The alkaline solution KOH acts as the electrolyte [69].

This type of battery can be commonly found in two different forms, depending on the application: in its sealed form in portable equipment, and in its flooded form in general industrial applications. In order to obtain a full-charge flooded Ni–Cd battery, it is necessary to apply a certain level of overcharging, with a very quick charge cycle. The discharge cycle is also very quick, due to significant lower internal resistance [96]. Ni–Cd batteries can inject their rated power during 2 h [69].

The Ni–Cd battery has good characteristics with respect to its long cycle life (more than 3500 cycles [69]), combined with low maintenance requirements [15]. Nevertheless, its cycle life is highly dependent on the DoD. It can reach more than 50,000 cycles at 10% of DoD.

Although the Ni–Cd battery presents some good technical characteristics, it has not had a major commercial success, mainly due to its considerable costs at more than 10 times of Lead-Acid [71]. However, Ni–Cd production gross is increasing, despite having a strong competitor such as NiMH in the field of alkaline batteries. Thus, the alkaline rechargeable battery market should rapidly expand [69].

Two major drawbacks of Ni–Cd batteries are their toxicity and the fact that they suffer from the memory effect. Actually, cadmium and nickel are toxic heavy metals which can cause health risk in humans [97,98]. For this reason, in November 2003, the European Commission drew up a proposal for new directives including recycling targets of 75% for this type of battery. With this new legal framework, energy storage in Ni–Cd batteries has an uncertain future.

2.3.3. Sodium–sulphur battery (NaS)

Besides being a relatively recent technology, NaS batteries are one of the most promising options for high power energy storage applications. The anode of this type of battery is made of sodium (Na), while the cathode is made of sulphur (S). Ceramic Beta-Al_2O_3 acts as both the electrolyte and the separator simultaneously [31]. During the discharge cycle, the metallic anodic material (sodium) is oxidized, releasing Na^+ ions, while the cathodic material is reduced, releasing S^{-2} sulphur anions. The electrolyte enables the transfer of sodium ions to the cathode where they combine with sulphur anions and produce sodium polysulphide NaS_x. During the charge cycle, the opposite reaction occurs; sodium polysulphide is decomposed into sodium and sulphur.

NaS battery cells are usually designed in a tubular manner where the sodium is normally contained in an interior cavity formed by the electrolyte. An important feature of this type of battery is its high temperature operation, around 350 °C [69]. At this temperature, sodium, sulphur and the product of the electrochemical reaction, NaS_x, are in liquid state, which allows a high reactivity of the electrodes. There are many concerns regarding the high temperature operation of the battery. To summarize: as the cell reactions are exothermic, the energy input required to maintain a proper operating temperature is low and therefore, the efficiency of the battery is not substantially reduced [99]. According to [31], the lower the electrolytic resistance of the battery, the better the performance due to the minimization of the energy lost in form of heat in the electrolyte.

One of the largest manufacturers of NaS batteries is the Japanese company NGK insulators [100]. One of its models can inject 50 kW of rated power for 7 h [70]. The energy density and the energy efficiency of this type of batteries are very high, 151 kW h/m^3 and 85% respectively [9].

Additional important features of NaS batteries are no self-discharge, low maintenance and their 99% recyclability.

2.3.4. Lithium-ion battery (Li-ion)

Li-ion batteries are widely used in small applications, such as mobile phones and portable electronic devices; therefore the annual production gross is around 2 billion cells [102]. In addition, this type of batteries attracts much interest in the field of material technology and others, in order to obtain high power devices for applications like electric vehicles and stationary energy storage.

The operation of Li-ion batteries is based on the electrochemical reactions between positive lithium ions (Li^+) with anolytic and catholytic active materials [101]. The cells of Li-ion batteries are made of anolytic and catholytic plates, filled with liquid electrolyte material. The electrode areas are delimited by a porous separator of polyethylene or polypropylene, which allows the transit of lithium ions. The catholytic material is usually based on lithium metal oxide, as lithium cobalate ($LiCoO_2$), while the anolytic material is graphite (C). The electrolyte is usually a non-aqueous organic liquid, such as PC, EC or DMC, which contains dissolved lithium salts such as $LiClO_4$.

The charging and discharging cycles of the battery are detailed as follows. During the charge cycle, Li^+ flows from the positive electrode, made of $LiCoO_2$, to the graphite sheets of the negative electrode [102,101]. The discharge cycle consists of the reverse process.

Since the performance and the range size of the battery are strongly related to the active materials of the electrodes and the electrolyte, there is a tremendous amount of research in the field of material technology nowadays [102–104,101].

As important features of Li-ion batteries, it is appropriate to mention their high energy density and specific energy, 170–300 W h/l and 75–125 W h/kg respectively [101]. Another major feature is their fast charge and discharge capability [105]. In fact, time constants (understood here as the time to reach 90% of the rated power of the battery) around 200 ms, with a relatively high round trip efficiency of 78% within 3500 cycles, have been reported [76]. These characteristics make Li-ion batteries good candidates for applications where the response time and weight are important. In addition, Li-ion batteries are mainly an option in short time scale applications, due to their relatively high daily self-discharge, between 1 and 5% [13,6,105].

Referring to the drawbacks of Li-ion batteries, it can be mentioned that, since their life time is dependent on cycle DoD, this technology is not adequate for the use in back-up applications where they may become fully discharged. In addition, maintaining a safe voltage and temperature operation ranges are essential aspects for this technology, due to its fragility. Indeed, protection circuits are required [13]. In addition, the use of flammable organic electrolytes raises issues about security and greenness.

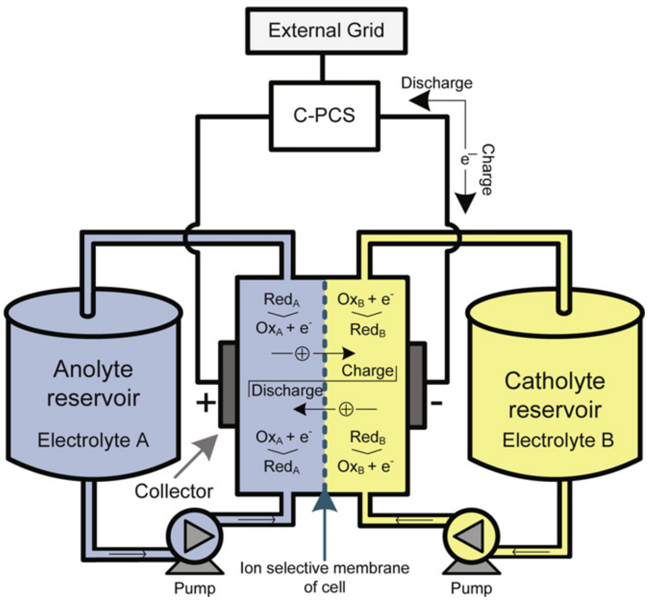

Fig. 3. Operation principle of Flow Battery Energy Storage System.

2.4. Flow Battery Energy Storage System (FBESS)

Flow batteries are a relatively young technology. Their operating principle is based on reversible electrochemical reactions that occur in a set of cells connected in series, parallel or both, in order to achieve the desired voltage level. Unlike conventional batteries, two different aqueous electrolytic solutions are contained in separate tanks. During the normal operation of the battery, these aqueous solutions are pumped through the electrochemical cell where the reactions occur [28,106]. Three types of commercially available flow batteries are considered in this article: Vanadium Redox Battery (VRB), Zinc Bromine Battery (ZBB) and Polysulphide Bromide Battery (PSB). Since their operation is based on reduction and oxidation reactions of the electrolyte solutions, these types of batteries are also called redox flow batteries. Their operating principle is presented in Fig. 3. As shown, during the charge process, the electrolyte A is oxidized at the anode, while the electrolyte B is reduced at the cathode. The discharge cycle consists of the reverse process.

One of the major advantages of flow batteries is that their energy capacity is easily scalable, since it depends on the volume of the stored electrolyte. This leads to lower installation costs the larger the system is [97]. As a result, energy and power capacity of flow batteries are independent characteristics: the power capacity of the system depends on the cell number and the size of the electrodes. But operating costs are not negligible, due to the control of electrolytic flows and pumps [28]. In this sense, the ZBB presents worse performance than a PSB and VRB, since a third pump is required for the recirculation of bromine complexes.

Other interesting features of flow batteries are their ability to become fully discharged without any damage, and their very low self-discharge, since the electrolytes are stored in separate sealed tanks. Therefore, redox flow batteries result as systems with a long life and low maintenance, able to store energy over long periods of time.

2.4.1. Vanadium redox flow battery (VRB)

The VRB stores energy in two tanks, an analytic and catholytic reservoir, containing sulphuric acid solutions. In the analytic reservoir, V^{2+}/V^{3+} are used as electrolytes, while the electrolytes V^{4+}/V^{5+} are used in the catholytic reservoir [20,63]. When an electrochemical reaction occurs, carbon electrodes enable the electron flow through the load, while the electrical balance is achieved by means of the migration of a hydrogen ion through the membrane which separates the two electrolytes. Since the products of chemical reactions remain dissolved in the electrolytes, the reverse process leads solutions to their initial state. Moreover, there is no danger of cross-contamination of the electrolytes, as they both contain the same type of metal ion.

The system life is about 15–20 years [62], with more than 1000 charge and discharge cycles at 100% of DoD [27]. However, while electrolytes do not require special maintenance, it is recommended to replace the separator membrane every 5 years [63]. The system can achieve an energy efficiency of 78% [61], and it results in relatively low cost to store large amounts of energy for long times. According to [107], the cost per kW h decreases as energy storage capacity increases, achieving costs as low as 150$/kW h for 8 or more hours of storage devices.

Referring to the drawbacks of the system, it is remarkable that its low specific energy and energy density, around 25–35 W h/kg and 20–33 W h/l respectively [33] reduce the potential uses of the battery in non-stationary applications.

2.4.2. Zinc–bromine flow battery (ZBB)

In ZBBs, two aqueous solutions, based on Zn and Br and stored in separate tanks, flow through electrolytic cells where the reversible electrochemical reactions are produced. During the discharge process, bromide ions Br^- are converted to bromine Br_3^-, in the positive electrode, which reacts with other organic amines and creates thick bromine oil that sinks to the bottom of the tank. Meanwhile, in the negative electrode, positive zinc ions Zn^{2+} are converted to metallic Zn. Reverse reactions to those described are carried out during the charge process of the battery. Cell electrodes are composed of carbon-plastic composite and are separated by means of a micro-porous polyolefin membrane [23,20].

Since the invention of ZBBs in 1970 by Exxon, this technology has evolved to the point that it is now commercially available in sizes of 1 MW/3 MW h for utility-scale applications [23], with the ability to provide its rated power for 2–10 h [108]. Indeed, large amounts of energy can be stored for long periods of time due to virtually no self-discharge of the battery [66]. Other important features of this technology are its relatively high specific energy of 75–85 W h/kg [67] (between 2 and 3 times that of Lead-Acid batteries), a high energy efficiency of 75–85% [28] and a longer cycle life than 2000 charge and discharge cycles at 100% of DoD without any damage [64]. In terms of greenness, these products are basically made of recycled plastics, allowing low cost production and high recyclability [66].

2.4.3. Polysulphide–bromide flow battery (PSB)

The operation of PSBs, also called regenerative fuel cells or Regenesys, are based on the electrochemical reactions between two salt-based electrolytes: sodium bromide (NaBr) and sodium pölysulphide (Na_2S_x). The electrolytes are separated by a polymer membrane which only allows the interchange of positive sodium ions [30,97,20,106]. During the charge cycle, bromide ions (Br^-) are transformed into tribromide ions (Br_3^-) in the positive electrode of the cell. In the negative electrode, dissolved sodium particles (S_4^{2-}) in the polysulphide electrolyte are reduced to sulphide ions (S_2^{2-}). The discharge cycle consists of the reverse process.

Regenesys Technologies built the larger system based on this battery type in 2003. The rated power and energy capacity of this system are 15 MW and 120 MW h respectively, which provide a duty cycle of 10 h [20,109]. The system has a modular design. Each module has 100 kW of rated power. The energy efficiency of the

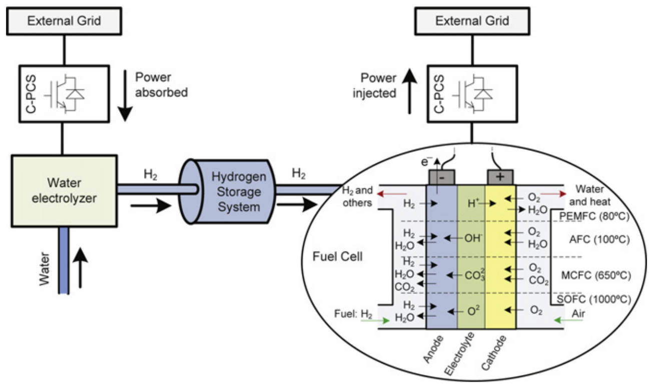

Fig. 4. Topology of regenerative fuel cell.

system is 75%, with a relatively long life, more than 15 years. The project budget was around 250 million dollars.

Since a PSB has practically no self-discharge, it is suitable for storing energy during long periods of time. Moreover, the chemical elements present in the battery are abundant in nature, and their costs are reasonable [20]. On the other hand, a tank failure would expel toxic bromine gas [97].

2.5. Hydrogen-based Energy Storage System (HESS)

Hydrogen can be obtained in various ways: by means of water electrolysis, from renewable energies such as solar or wind installations, gasifying biomass, coal or fuel (which is the most common option) [110,111]. When hydrogen is produced from wind power plants, it can be stored in order to be used directly in fuel cells, or transported to users through pipelines to produce electricity [112].

When hydrogen is stored, the technology used is known as Regenerative Fuel Cell (RFC) [113,11]. As shown in Fig. 4, it is composed of the following components: a water electrolyzer system, a fuel cell system, a hydrogen storage and a power conversion system. This technology is responsible for carrying out the electrochemical transformations in order to store energy in the form of hydrogen and inject it as electricity into the grid, when required.

As presented, electrolyzers are key parts of RFCs. By means of these devices, water is electrolytically decomposed into hydrogen and oxygen. There are many types of electrolyzers, from common technologies such as Alkaline electrolyzers [112], to more modern types like Polymer Electrolyte Membrane (PEM) electrolyzers. PEM electrolyzers were invented in 1970, but hydrogen production by means of this type of technology is currently considerable, reporting production volumes up to 10 N m^3/h [114]. The electrolyzers are classified by their type of electrolyte, liquid or solid. The use of solid electrolytes allows PEM electrolyzers to generate hydrogen at suitable pressures (200–6000 psi [11]) in order to store it in tanks or in metal hydrides.

In fact, hydrogen can be stored in many forms [110,13,115]: as gas in metal tanks (or other composite materials like carbon fiber or polymer) at pressures up to 350 bar, or in metal hydrides. Storing hydrogen in metal tanks may be suitable for large volume applications for long term storage (more than 30 h), while storing hydrogen in metal hydrides is suitable for storage periods longer than 3 h [111]. Other less developed storage technologies include the liquefaction of hydrogen and the storage in carbon nanofibers.

Similarly to the electrolyzers, there are many types of fuel cells for stationary and distributed generation purposes [116,117], depending on their electrolytic material. In Fig. 4, the Polymer Electrolyte Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) are detailed. The PEMFC is the most used technology. Its low operation temperature (between 50 and 100 °C), maintenance and corrosion, as its electrolyte is solid, are important characteristics of this type of fuel cell. On the other hand, since the catalytic material is platinum, the cost of the device increases significantly. In addition, this technology is affected by hydrogen impurities, which affect its life.

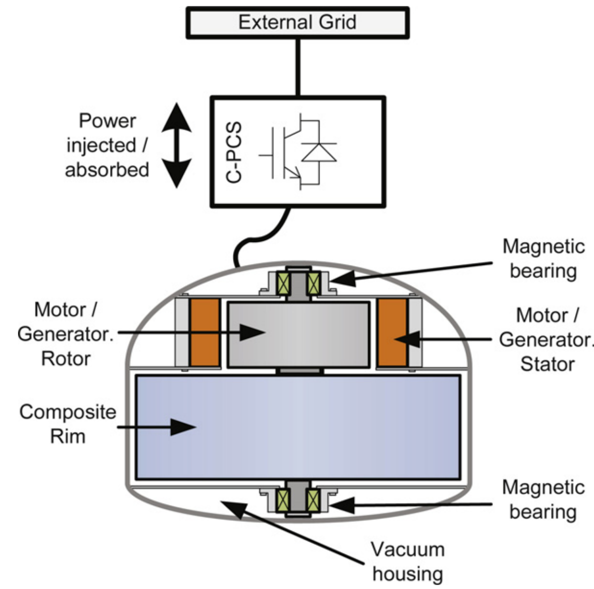

Fig. 5. Topology of Flywheel Energy Storage System.

The sizing of the stack depends on the type of technology used, leading to 100 kW PEMFC stacks or 2 MW SOFC stacks. Fuel cells are noted for their good dynamic behavior, allowing a quick start-up, even at partial load. No acoustic emissions are noted during their operation and they only discharge water as a product [113].

As they are flow batteries, RFC power and energy capacity are not related characteristics. In addition, since they are designed in a modular manner, high energy systems with more than 100 MW h and with high peak power, more than 10 MW, can be achieved. Their practically zero self-discharge (depending on the type of hydrogen storage) allows these systems to store energy for long periods of time. In terms of their useful life and cycle life, they are estimated at more than 15 years and 20,000 charge and discharge cycles (at 100% of DoD) respectively [5,11,111]. Finally, notice that one of the major drawbacks of a RFC is its low energy efficiency, about 42%, due to the relatively low energy efficiencies of the fuel cell and the electrolyzer, about 60% and 70% respectively [58].

2.6. Flywheel Energy Storage System (FESS)

A FESS is an electromechanical system that stores energy in form of kinetic energy. A mass rotates on two magnetic bearings in order to decrease friction at high speed, coupled with an electric machine. The entire structure is placed in a vacuum to reduce wind shear [118,97,47,119,234]. The scheme of the system is presented in Fig. 5.

Energy is transferred to the flywheel when the machine operates as a motor (the flywheel accelerates), charging the energy storage device. The FESS is discharged when the electric machine regenerates through the drive (slowing the flywheel). In fact, the energy stored by the flywheel is dependent on the square of the rotating speed and its inertia. Commercially, the two major types of machines used for flywheels systems are the axial-flux and the radial-flux permanent magnet machines. Apart from the permanent magnet machine used in almost all flywheels, there is also the possibility of using synchronous reluctance or induction machines.

In general, flywheels can be classified as low speed or high speed devices. The first operates at revolutions per minute (rpm), measured in thousands (this class of flywheel uses steel as the main structural material in the rotor), while the latter operates at rpm measured in tens of thousands (this class of flywheel uses a rotor made of an advanced composite material, such as carbon-fiber or graphite [120,47]). The energy density of the flywheel depends on the product of a shape factor, taking the inertia of the rotating disk into account, and the permissible tangential strength of the disk, which depends on its material. Moreover, the maximum specific energy of the system is determined by the ratio of the energy density and the density of the material of the rotating disk [121,120]. Thus, the choice of the material is a key point in the system performance, since high-strength but lightweight materials are required. Moreover, the rated power of the system is limited by its C-PCS.

On the one hand, a FESS presents good features regarding high efficiency (around 90% at rated power), long cycling life, wide operating temperature range, freedom from depth-of-discharge effects, higher power and higher energy density [118,97,122,43]. On the other hand, flywheels present relatively high standing losses. Self-discharge rates for complete flywheel systems are about 20% of the stored capacity per hour [13]. This is the reason why flywheels are not adequate devices for long-term energy storage. The largest available kinetic energy storage device is manufactured by Piller Power Systems [44]. This system is designed to operate within a speed range of 3600 rpm to 1500 rpm. Its energy capacity is about 19 MWs and can deliver 10 s of ride-through at 1.65 MW load and proportionately a longer ride-through at lesser loads.

2.7. Superconducting magnetic energy storage (SMES)

The SMES system is a relatively recent technology. The first system based on this technology was built in 1970 [43]. Its operation is based on storing energy in a magnetic field, which is created by a DC current through a large superconducting coil at a cryogenic temperature.

The energy stored is calculated as the product of the self-inductance of the coil and the square of the current flowing through it [78]. Thus, the characterization of the coil has a central role in the system design. Depending on the system operating temperatures, superconducting coils can be classified as: High Temperature Coils (HTS), which work at temperatures around 70 K, and Low Temperature Coils (LTS), a more mature technology, with working temperatures around 5 K. A balance between cost and system requirements determines the technology used.

The maximum current that can flow through the superconductor is temperature dependent. Indeed, the lower the operating temperatures, the higher the operating currents that can be achieved. According to [6], flux densities around 10 T at 4.2 K have been experimentally reported, allowing energy densities of 40 MJ/m^3. Therefore, higher energy densities than those of flywheels and conventional batteries can be obtained.

The cooling system must be considered as a core element of the system, since it is fundamental to obtain a superconductor coil in its cryogenic state [123]. In this sense, the system has two cryocoolers, the first is responsible for cooling the superconductor coil by means of liquid helium or nitrogen bath, and the second is required to cool shields outside the bath [124]. Fortunately, the energy required for these cooling systems is much smaller than the energy stored in the system. Therefore, and taking into account other energy losses such as those due to the C-PCS, SMES systems have very high energy efficiencies up to 90% [78]. Indeed, a cryocooler can keep the system operating temperature at 20 K with a lower power consumption than 20 W/s [125].

Concerning the C-PCS, two different types of power converters are considered, the VSC and the CSC [79,78]. Even though the active

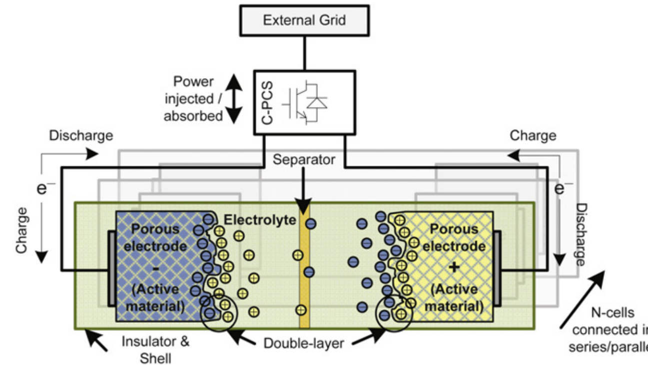

Fig. 6. Energy storage system based on a supercapacitor.

and reactive power can be properly controlled with both power electronics-based converters, a reactive power management with a very low or even zero current in the coil is only possible with VSC. On the other hand, CSCs are able to inject higher reactive currents. In addition, VSC control is usually more complicated than a CSC one, due to the presence of a DC/DC chopper.

Finally, it is appropriate to highlight some important features of SMES systems. Undoubtedly, a defining feature of these systems is their ability to inject or absorb large amounts of energy in a very short time. According to [41], the power injection of a 1 MW/1 kW h SMES can be increased in 200 kW in only 20 ms. Other experimental studies show similar results [126]. The energy capacity of these systems ranges from 100 kW to 10 MW, and it is possible to inject their rated power only for a few minutes before being discharged [78,43]. In addition, SMES systems have a very long cycle life of tens of thousands of cycles [78]. Despite their good technological features, there are actually very few SMES systems built, mainly due to their high cost [6]. According to [4], the capital power cost may vary between 1000 and 10,000$/kW.

2.8. Supercapacitor energy storage system

Supercapacitors are also known as ultracapacitors or double-layer capacitors. Like batteries, supercapacitors are based on electrochemical cells which contain two conductor electrodes, an electrolyte and a porous membrane whereby ion transit between the two electrodes is permitted. However, no redox reactions occur in the cells, because the operating voltage is lower, in order to electrostatically store charge on the interface between the surfaces of the electrolyte and the two conductor electrodes [127,51,128]. In fact, this structure creates two capacitors (due to both interfaces, electrolyte – negative electrode and electrolyte – positive electrode), and for this reason, they are called double-layer capacitors.

The energy stored in the capacitors is directly proportional to their capacity and the square of the voltage between the terminals of the electrochemical cell, while the capacity is proportional to the electrode-surface area and inversely proportional to the distance between the electrodes. Therefore, the main difference between capacitors and supercapacitors is the use of porous electrodes with high surface-areas by the latter ones, providing higher energy densities to the system [129,128].

Due to their low-cell voltage (about 3 V), the desired voltage and capacity of the supercapacitor are achieved by the series and parallel connection of a set of cells [6]. The topology of a system based on a supercapacitor is shown in Fig. 6.

There are two types of supercapacitors depending on the design of the electrodes [130,85,128]: symmetrical and asymmetrical supercapacitors. Unlike unsymmetrical ones, symmetrical supercapacitors utilize the same material for their positive and negative

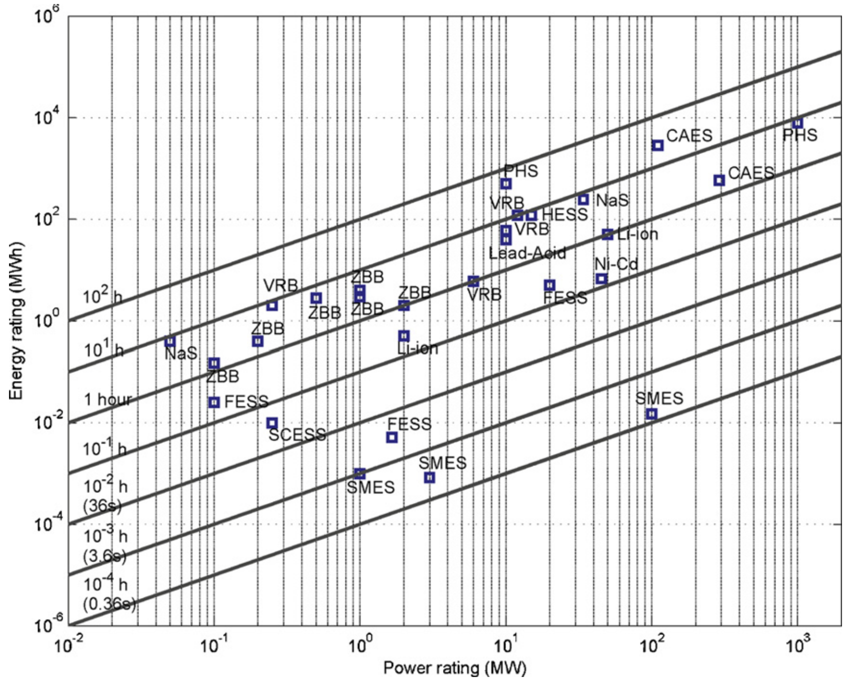

Fig. 7. Discharge time at rated power of ESS, according to the data collected in Table 1.

electrodes. Moreover, further classification can be made for electrodes based upon their materials [131]. In this sense, it can be distinguished between activated carbon electrodes, metal-oxide electrodes and electronically conducting polymer electrodes. Activated carbon electrodes are commonly used in commercial systems due to their low cost and high capacity (up to 5000 F [83,51]). In fact, activated carbon electrodes provide capacities from 100 to 1000 times per unit volume over conventional electrolytic capacitors [132]. Concerning the electrolyte, since its breakdown voltage limits the voltage of the supercapacitor cell, the proper choice of its material is very important. There are several types of electrolytes. To summarize, they can be classified into aqueous electrolytes and organic electrolytes, which are most common [128].

As mentioned, electrolyte and electrode materials have a fundamental influence on the energy and power capacity of the supercapacitor, as well as its dynamic behavior. Actually, the product of the equivalent resistance of the electrolyte and the capacity of the supercapacitor determine its charge and discharge time constants. This equivalent resistance is very small (less than 1 milliohm [133]), therefore short time constants can be achieved. In addition, power densities 10 times higher than batteries can be achieved. These features, combined with the high self-discharge of the system (which can be 20% of its rated capacity in 12 h, due to the non negligible equivalent resistance of the contact between the electrolyte and the electrodes [65,134]), define the system as a candidate for short time scale applications with short time responses.

Other important features of supercapacitors are their long life, more than 5×10^4–10^5 cycles with virtually no maintenance and energy efficiency of about 75–80% [84]. Charge and discharge cycle times of the system are about 1–30 s at rated power, while the specific power and energy power of the system are very high, 2000–5000 W/kg and 20,000–30,000 W/m^3 respectively. However, its specific energy and energy density are low, 2–5 W h/kg and 10,000 W h/m^3, due to the difficult access to the porous surface of the electrode by ions [40,53]. Finally, it can be noted that the most important drawback of supercapacitors is their high cost, estimated at 5 times that of Lead-Acid battery cost, 9500$/kW h [48].

3. Applications of the storage technologies in wind power

This section details the potential applications of ESS in wind power. Each technical issue, concerning different aspects related with the management of wind power plants and their integration into the electrical network, has been identified and defined according to [75,135,4,71,26,2,136]. In addition, the definition of these aspects is complemented by a brief discussion on the ESS role in each case. Finally, a review of several publications concerning the ESS applications in wind power is summarized in Table 3.

3.1. Fluctuation suppression

Fast output fluctuations (in the time range up to a minute) of the power of wind generators can cause network frequency and voltage variations, especially in isolated power systems, and thus impairing the power quality [226]. In order to mitigate the effects of power fluctuations, an ESS can be used. Storage technologies suitable for this application present high ramp power rates and high cycling capability, since fast power modulation and continuous operation are required. Thus, batteries (excluding conventional Lead-Acid batteries), flow batteries, and especially short time scale energy storage like supercapacitors, flywheels and SMES are well suited for this service.

A widely accepted solution to mitigate the power fluctuations of a wind turbine driving a DFIG is to include an ESS in the dc-link of the back-to-back converters of the machine. This storage device is equipped with a control which interacts with the turbine's and other controls in order to optimize the net power delivered to the external grid by the entire system. This is the case presented in [160]: a supercapacitor connected to the dc-link of a wind generator through a two-quadrant dc–dc converter. Two levels of control are defined, the high level (wind farm supervisory controller), which is in charge of coordinating the set points of each wind generator, and the low level, which details the vector controllers of the converters of each wind generator. As a wind turbine controller, the C-PCS of each storage device receives the set point calculated by the high level controller, and manages the power injection or absorption by means of computing the

Table 3
Overview of publications regarding the uses of ESS in wind power.

	Full power duration of storage	PHS	HESS	CAES	VRB	ZBB	PSB	NaS	Lead acid	Ni–Cd	Li-ion	SMES	FESS	SCESS
Fluctuation suppression	≤1 min				[137–140]	[137, 64]	[137]	[141]		[142, 143]	[37, 144]	[126, 145, 146, 125, 147–149]	[150–158]	[159, 84, 160, 154]
LVRT	≤ 1 min				[138, 161]	√ [a]	√ [a]	[162, 70, 163]	[162, 163]	[162, 163]	[162, 163]	[159, 164–166, 147, 167, 168, 43, 149]	[43]	[159, 85]
Voltage control support	≤ 1min				[137, 138, 18, 139]	[137]	[137]	[169, 162]	[169, 93, 170, 171]	[169, 142, 143]	[169, 162]	[126, 167, 43, 172]	[43, 155]	[128]
Oscillation damping	≤1 min		[173]		[137]	[137]	[137]	[174, 175, 163, 176]	[174, 176, 163]	[174, 176, 163]	[174, 176, 163]	[177, 174, 167, 178, 168, 172]	[179, 180]	[132]
Spinning reserve	1–30 min	[90]	[181]	[182]	[137, 183, 18, 139, 140]	[137, 64, 183, 18]	[137, 183, 18]	[184, 185, 31]	[184, 185, 93, 186]	[16, 184, 185]	[184, 185]	[78]	[187, 18]	
Load following	min–≤10 h	[188–192]	[193, 181, 194, 195, 184, 196–198]	[199–201]	[202, 21, 203, 18]	[204, 203, 108, 18]	[18]	[203, 205–207, 31]	[208, 207, 203, 93, 186]	[203, 207, 142]	[207]			
Peak shaving	1–10 h	[209, 57, 188, 210–212]	[213, 194, 195, 112]	[18, 214]	[203, 215, 216]	[16, 203, 108]	[216]	[65, 203, 207, 217]	[218, 203, 207, 93]	[203, 207]	[207]			
Trans. curtailment	5–12 h	[209, 219, 90, 220]	[113, 194, 221]	[222, 220, 214]	[223]	√ [a]	√ [a]	√ [a]						
Time shifting	5–12 h	[219]	[5, 195, 112]	[224]	[26]	[16]	√ [a]	[203]						
Unit commitment	hours–days	[188]	√ [a]	[182]										
Seasonal storage	≥4 months	[225]	[221, 196]											

[a] Although the storage technology is suitable for this application, dedicated studies are not listed here.

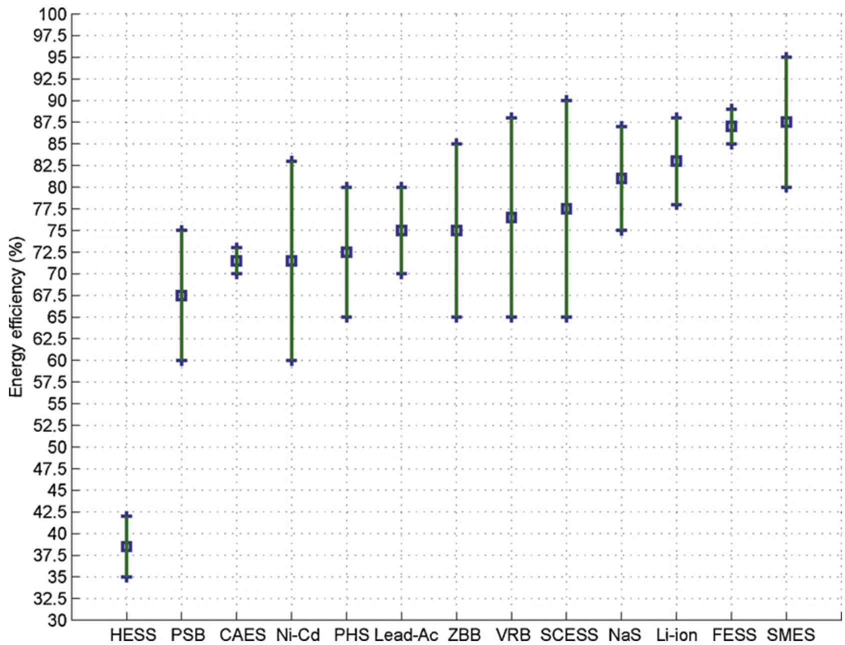

Fig. 8. Energy efficiency of ESS's, according to the data collected in Table 2.

difference between this signal and the actual active power of the wind generator.

Flywheels are also under study for complementation of the dc-link of DFIG wind turbines. Since the operating principle of this technology is highly related to the power management of a motor/generator, the control theory of electrical drives plays a key role in these studies. In [150], three techniques of sensor-less vector-controlled induction motors driving a flywheel are compared. In addition, control theories based on the Model Reference Adaptative System (MRAS) for the design of speed estimation algorithms, as well as flux weakening aspects, motivated by the high speed of the flywheel are taken into account [156,157]. In addition to the use of induction machines, permanent magnet and switched reluctance machines are studied for flywheel storage devices [158].

As noted at the beginning of this section, the effects of power fluctuations of wind turbines regarding power quality issues, are remarkable, especially in isolated systems. Related to this problem, the combination of storage systems, like flywheels, supercapacitors or batteries in hybrid systems with offshore wind generation, diesel and photovoltaic generation, is proposed by [154].

Other studies [146,125] propose the use of SMES in order to perform the task of fluctuation suppression, providing storage at the PCC of the wind farm to the network. In this configuration, the rated power of SMES reaches several MW. For instance, a 15 MW h-60 s SMES is proposed in [148], in order to smooth the power fluctuations of a 100 MW wind power installation. In this case, the wind power plant is connected to the external grid through a back-to-back DC link. To conclude, it is noted that by means of the management of charge and discharge rates of SMES, the capacity of the power converters of the wind power plant can be reduced by 60%. Issues such as SMES capital costs, as well as power losses, due to maintaining low temperature of operation and leakage magnetic fields, have to be taken into account.

3.2. *Low voltage ride through (LVRT)*

The voltage control of wind power plants at the point of connection with the external grid during voltage dips, is carried out in order to prevent the wind power plant from being disconnected, which could cause the collapse of the network. For this reason, grid codes require wind power plants to withstand voltage dips up to 0% of the rated voltage and for a specified duration. These requirements are known as LVRT requirements. Since many technologies of wind generators include power converters, it is possible to adjust the reactive power injected into the grid during these situations [227–229]. Therefore, energy storage is not necessary in these situations, but may protect the dc-link of the converters from over-voltage.

As in the case of fluctuation suppression service, the suitable storage systems for this application present high ramp-up rates enabling a fast power modulation. Therefore, batteries, flow batteries, and short time scale energy storage like supercapacitors, flywheels and SMES are well suited for this application.

In [159], the dc-link of the set of back-to-back converters of a wind turbine driving a DFIG is complemented by supercapacitors. Numerous simulation results show the improved ride-through capability of the system with energy storage support. Fuzzy logic control techniques are suggested to manage the interaction between the C-PCS of the supercapacitors and the wind generator converter controllers, dumping the voltage variations of the dc-link during these disturbances.

The use of these control theories is also proposed in [164]. This article deals with the SMES implementation in a system with fixed speed wind turbines equipped with pitch control. The SMES is connected to an ac cable through a six pulse PWM rectifier/inverter, using IGBTs and two quadrant dc–dc choppers. Both converters are linked by a dc-link capacitor. The effectiveness of pitch control and the SMES in the voltage stability of the system under persistent fault situations, caused by the inability of reclosure the circuits breakers of the system, is studied. The improvement of the voltage stability with SMES under LVRT situations is discussed also in [149].

Another C-PCS of SMES is presented in [147]. In this case results as a combination of series and parallel inverters. Their dc-links are connected to a two-quadrant dc–dc converter with a dc-link capacitor and a superconducting coil. While the series converter is responsible for regulating the voltage oscillations of the wind generator, the parallel converter simultaneously controls active and reactive power in order to damp the oscillations of the tie-line power flow. The dc bus voltage is properly maintained by controlling the superconducting coil.

As well as SMES and supercapacitors, batteries and flow batteries are also proposed for LVRT applications. For instance, in [161], a VRB is connected to a dc-link of a direct drive wind turbine driving a permanent magnet synchronous generator. The control of the dc–dc converter of the VRB enables an improved capability of the generator under LVRT situations.

3.3. Voltage control support

Wind generators, and especially squirrel cage induction generators, consume large amounts of reactive power. The control of the reactive power flow in an electrical network is crucial for maintaining proper levels of voltage in the system. Therefore, various technologies of wind generators have been developed so far [230]. Wind turbines driving a DFIG or full power converters synchronous generators are ways to transfer all or a part of power generated to the network via power converters. With these topologies, the reactive power control of wind generators and hence the voltage control at their connection point is feasible. Also, with the inclusion of energy storage support, the dynamics of the voltage control can be improved.

Batteries, flow batteries, and short time scale energy storage like supercapacitors, flywheels and SMES, are well suited for this application, mainly because of their high enough ramp rates. Since the storage device must be able to manage both active and reactive power, the C-PCS of the storage device becomes essential. In this sense, FACTS/ESS systems are proposed to carry out this task properly, e.g. [155] proposes a Distribution Static Synchronous Compensator (DSTATCOM), coupled with a flywheel in order to mitigate voltage stability problems due to the introduction of wind generation in the electric system. Since the dc-link of the STATCOM is strengthened by the energy storage support, it can exchange both active and reactive power.

In [169], a STATCOM/BESS is connected to a wind self-excited induction generator, not only to manage reactive power, but also to compensate harmonic currents and load changes of an isolated system. As a result, the efficiency and the availability of the system are enhanced.

It is important to note that active power control features depend on the storage technology. In this sense, a SMES system presents very good characteristics for a fast injection or absorption of active power; e.g. [126] shows field test results of SMES, where a 16.6 ms response time in the step input of both active and reactive power can be seen.

3.4. Oscillation damping

The system stability against disturbances may be compromised with high penetration levels of wind power to the grid. For this reason, wind power plants will be required in future grid codes for helping generators of an interconnected network not to lose synchronism against perturbations. Thus, wind power plants will be required to mitigate these power oscillations of the system by absorbing or injecting active power at frequencies of 0.5–1 Hz [26].

Many storage technologies are suitable for this service. The time of injection / absorption of active power by the storage device is about one minute, therefore high ramp-up rates and response time are preferable. Thus, HESS, flow batteries, batteries, and short time scale energy storage like supercapacitors, flywheels and SMES are well suited for this application. System stability aspects are usually dealt with by modal and frequency domain analysis. Flywheels are proposed to be included in the network in favor of better dynamic performance under disturbances [179,180]. For instance, in [179], a general multimachine system is considered a study case in which a method for an optimal installing location of flywheel devices is performed in order to damp the low frequency power oscillations of the system.

The SMES system capacity to quickly manage large quantities of active and reactive power simultaneously is investigated in [167,178,168,172]. Wind power plants with SMES are required to provide oscillation damping of power flows in an interconnected system in these studies. A frequency domain analysis, based on linearized system models using eigenvalue techniques, as well as time domain analysis, based on a more detailed non-linear system models under disturbance conditions, are proposed. These system disturbances may be caused by the disruption of local loads, wind gusts, fast wind fluctuations or short-circuits. Control techniques are a key aspect here. Since system uncertainties must be taken into account, e.g. various generating and loading conditions, parameter variations and non-linearities, the application of linear controllers is not always appropriate.

In this regard it is interesting to note the methods described in [178]. Here, a robust non-linear control of SMES is proposed, which bases its operation on the addition of a power disturbance in a wind-based network with oscillating power flow in order to reach a net constant power flow in the system. The consideration of uncertainties of the system in SMES control provides a much adequate behavior of its response.

Not only theoretical studies have been done, but also experimental tests, [174]. Here, the benefits of the inclusion of storage devices for improving the system stability are discussed. It is concluded that power oscillation damping control is more robust against variations of power system conditions in the case of managing active and reactive power by means of SMES and batteries actuation.

3.5. Spinning reserve

According to [231], spinning reserve is defined as the unused capacity that can be activated by the system operator's decision, and which is provided by synchronizing with the network devices capable of affecting the active power of the system. Since a secondary and tertiary reserve can be activated by the system operator's decision, they are regarded as spinning reserves. Therefore, according to the definition, wind power plants are required to regulate their active power for up to 30 min, in order to provide a frequency support to the system.

There are many storage technologies which are suitable for this application: flywheels, SMES, batteries, flow batteries, HESS, CAES or PHS installations. Batteries and flow batteries have been the subject of study in numerous publications for providing spinning reserve capability in wind power plants.

The provision of spinning reserves plays a key role, especially in isolated systems [184,185]. In this sense, BESS is proposed to be included in an isolated wind-hydro-gas system in [185]. The management, as well as the optimal size of batteries, are the main concerns of study in order to obtain the maximum economical benefit by the owner of the storage device while fulfilling the spinning reserve function. A numerical optimization problem is proposed in order to optimize the economical benefit, given by the difference between the revenues, due to the frequency control reserves availability and the storage energy sales income, and costs, due to maintenance and investments in storage technologies. The experience results of providing spinning reserve by a 6 MW to 6 MW h VRB in a 30.6 MW wind power plant are reported in [140]. In conclusion, it is important to remark that wind generator power oscillations for a period of 30 min are reduced by a factor of 3. The estimation of the battery charge state by means of cell voltage measurement favors the VRB operation.

Flow batteries in spinning reserve applications have been extensively reported in literature. In fact, short response times and the

capacity of being overloaded make these system superbly well suited for this application, even having advantages over other conventional facilities, like fossil fuel power stations [183].

3.6. Load following

In this service, storage technologies are required to provide energy in the time frame of minutes to 10 h [75]. Due to the stochastic nature of wind, the wind power plant output would not match the power demand. This leads to various technical and economic problems regarding the operation of the electrical system. Technical issues, like voltage and frequency variations due to imbalances between electricity generation and demand, limit the renewable technologies' penetration into the electrical network. Regarding economic issues, it should be remarked that some regulatory frameworks specify economic penalties to wind power plants for not meeting generation bids, on account of wind forecasting errors. In this sense, the ESS can be used to store and inject electrical power for hours. Batteries, flow batteries, as well as HESS, CAES or PHS installations are well suited for this application.

Probably, a glaring example of the feasibility of combining wind with battery solutions is a wind power installation case in Futumata (Japan), where a 34 MW NaS battery bank is used to level the production of a 51 MW wind power plant [206]. Proper management of the energy of the battery is essential, not only regarding technical issues (e.g. shortage/surplus of the battery), but also from an economic point of view. In this sense, in [205], a control algorithm that optimizes the economic benefit of the system, minimizing the storage in peak-demand hours when the market price of the energy is high, is developed.

In this case, control and dimensioning aspects of flow batteries are discussed in [202,21,204]. As a conclusion of these works, it can be said that many techno-economic benefits for the electrical system derives from a proper solution of these aspects. Proper control of the batteries improves the predictability of wind power plants and therefore, the associated costs for their grid integration regarding reserve requirements can be decreased, since great precision in matching their output with their forecast power is achieved. According to [204], 34 MW and 40 MW h of storage capacity are required to improve the forecast power output of a 100 MW wind plant (34% of the rated power of the plant) with a tolerance of 4%/pu, 90% of the time.

Techno-economic analyses are addressed in [199,56,201], regarding CAES use in load following applications. As an example, [201] presents a stochastic electricity market model in order to study the effects of high penetration of wind power in the electrical systems, as well as the economical viability of including CAES solutions. With system minimization costs as criteria, there is an optimization problem which takes into account aspects, such as transmission capabilities of the system, energy prices, technical characteristics of the generating plants, electricity demand profiles, investments costs and power reserve requirements. Important conclusions (taking into account the German electricity market), include an economic advantage of CAES to conventional peak thermal plants in a scenario with high penetration of wind power.

Finally, it is important to remark that hydrogen-based storage technologies are considered as one of the most promising technologies in load following applications. Actually, several demo projects have been developed as a proof of concept concerning stand-alone systems with wind, photovoltaic generation and hydrogen storage [193,195,196]. These projects focus on developing power management algorithms, using the excess of energy for creating hydrogen in an electrolyser and using it in a fuel cell in order to inject power to the system when required. The evaluation of the system operation shows the technical feasibility of such isolated schemes with hydrogen support.

3.7. Peak shaving

This service falls within the time frame of 1–10 h. The operating strategy for the storage devices is to store cheap energy at off-peak demand periods (overnight), and to inject it into the network during periods of high electricity demand, and hence soften the typical mountain and valley shape of the load curve.

Well suited ESSs for peak shaving applications are batteries, flow batteries, CAES, HESS and PHS. Regarding the batteries, numerous techno-economic studies display the feasibility to store energy during off-peak demand hours and sell it at peak demand periods.

In [203,217], the use of NaS batteries for this application is discussed. While technical benefits for the electrical system in a real case, as well as details referring to the design of the C-PCS of the battery, are presented in [217], an interesting techno-economic analysis of BESS is discussed in [203]. In conclusion, in order to define an available economic operation of BESS in the Spanish energy market, the sale price of the battery energy is fixed at 0.22–0.31 €/kW h (actually, the energy price is around 0.04–0.05 €/kW h). Therefore, it is concluded that BESS operators should receive subsidies, due to the emissions that would imply the use of conventional fuel plants for peak shaving applications, in order to make its use economically profitable. The selling price of BESS energy is substantially lower than that of a RFC system. According to [213], in order to make a RFC economically viable to operate with a wind power plant, it would imply fixing its energy selling price at 1.71 €/kW h in the Spanish case, due to the low energy efficiency of the storage technology and the high cost of its components. Therefore, compared with the selling price of the energy injected by batteries, the selling price of the energy injected by hydrogen-based technology is around 5–8 times higher. This is one of the main challenges regarding the inclusion of hydrogen-based storage systems in the network.

Without a doubt, PHS is considered to be one of the most well suited storage systems in order to achieve high penetration levels of wind power in isolated systems. Indeed, wind-hydro systems have been studied, amongst other publications, in [188,211,212,232]. A techno-economic study of the viability of wind-hydro systems in providing power during peak load demand periods is performed in [211]. The results show an excellent technical and economic performance. It can be concluded that the integration of wind power plants in the isolated study case can be increased by 9%, allowing to a penetration level of 20%. In addition, a significant reduction of CO_2 emissions through the use of PHS installations instead of using fuel peak power plants is highlighted in [57]. However, regarding dynamic security issues of the system operation, it can be concluded that it may be appropriate to add some more technologies in order to provide spinning reserve to the system [188].

3.8. Transmission curtailment

In this application, storage technologies are required to provide energy in the time frame of 5–12 h. Due to several reasons, such as the need for ensuring the stability of the electrical system or technical limitations in power transmission lines, wind power plants have to be disconnected. In this sense, an ESS can store energy for hours and inject it in a controlled manner according to the capacity of transmission lines and stability issues, and thus, avoiding the disconnection of wind turbines. Well suited ESS for this application are flow batteries, CAES, hydrogen-based systems and PHS installations.

Studies regarding wind-hydro systems and CAES installations for transmission curtailment applications are considered by [209,222,90,214]. In general, wind-based isolated systems or systems connected to weak grids are considered to display the most interesting scenarios. Findings agree with the idea of including ESS

in highly renewable penetration systems with the aim of reducing wind curtailments, backup power, transmission losses, ensuring security of supply, saving update costs and avoiding the building of new transmission lines.

Finally, since hydrogen can be created by means of rejected wind power, hydrogen-based storage systems are considered a promising technology to be included in wind power applications. Once the hydrogen is stored, it can be used in different ways: either to generate electricity in fuel cells and inject it into the network during periods of peak power demand or for other uses, such as the field of mobility. As introduced to the previous section, the main challenges for the inclusion of hydrogen-based storage systems are related to the uncertainty of their economic viability (owing to the high system costs and its low energy efficiency) and the dependence of high hydrogen market prices [113,194,221,220].

3.9. Time shifting

In time shifting services, storage technologies are required to provide energy in the time frame of 5–12 h. In this case, ESS is required to absorb all the energy from wind power plants during off-peak demand periods, supplemented with cheap power bought from the network if necessary, and selling it during peak-power demand periods, thus avoiding the activation or update of other conventional peak power generation plants. Flow batteries, CAES, PHS installations and hydrogen-based storage technologies are well suited for this application.

In [224], the effects on the operation of electrical networks considering bulk energy storage capacity and wind power plants are discussed. In this sense, many operating strategies for wind-ESS are considered. One of the most interesting study cases is based on charging the storage device continuously for 12 h period (low demand period) and injecting its power in a controlled manner during the following 12 h (high demand period). As a conclusion, the fact is highlighted that time shifting services by means of ESS inclusion into the network are not economically viable without any kind of subsidy, due to high investments costs of the technologies (in this case, CAES systems is the most favorable technology) and relatively low energy efficiencies (depending on the technology). Regarding environmental aspects, ESS should be able to inject power during the entire high peak demand period, otherwise the operation of base load plants would be increased, with a consequent increase of CO_2 emissions.

3.10. Unit commitment

In unit commitment services, storage technologies are required to provide energy in the time-frame of hours to days. Due to the uncertainties regarding mesoscale variations of the wind, it is hard to manage the commitment of wind turbines in order to meet the estimated demand at all times. Also, the introduction of wind power plants into electrical systems motivates the need to maintain a certain level of energy reserves in order to compensate forecast errors. Therefore, the introduction of high capability ESS into the network may be useful to fight the effects of uncertainties in wind forecasting and to reduce system energy reserves during its normal operation. Large scale energy storage systems are suitable for this application: CAES and PHS installations, as well as hydrogen-based storage technologies.

This topic is addressed as a numerical optimization problem, in which the objective function is to minimize the operation costs of the electrical network, so as to maximize the return of the investments in including ESS [188,182]. For instance, in [182], the unit commitment problem is formulated in a power system with wind generation and CAES. The benefits of including CAES solutions, in order to reduce the operation costs of the electrical network by means of allowing the use of wind energy in charging this storage technology when the energy is not required by the system, and thus avoiding the disconnection of the wind turbines, are discussed.

3.11. Seasonal storage

In this application, ESSs capable of storing and injecting energy during periods in the time frame of months are well suited. Storing energy for long periods of time can be useful in systems with large seasonal variations in the level of generation or consumption. Clearly, only those storage technologies with a very large energy capacity and no self-discharge are eligible, such as large PHS installations or hydrogen-based solutions.

In cases where it can be technically interesting to include seasonal storage, and taking into account the investment costs regarding the installation of wind turbines and storage systems based on hydrogen, it may look favorable to oversize wind power plants in order to reduce the size of the storage reserves [221]. However, this would increase the non-utilized wind power capacity range and hence decrease the efficiency of the system. On the other hand, the energy costs of the system would be reduced.

A demo project regarding seasonal storage by means of hydrogen-based storage technologies in a stand-alone system is described in [196]. It must be noted, that although storing energy during long periods of time is technically feasible due to no leaks in the hydrogen storage tank, the use of the RFC must be limited, in order just to store the excess productions of wind power, in favor of minimizing the losses of the system, since the energy efficiency of RFCs is very low.

4. Conclusions

In this paper, the operating principles as well as the main characteristics of several storage technologies suitable for stationary applications have been described. In addition, a summary of potential ESS applications in wind power have been defined and discussed according to an extensive literature review. In conclusion, it is worth pointing out that several benefits for the operation of the power system considering wind power plants as well as some considerations can be achieved:

- High power ramp rates of some systems such as SMES, flywheels or supercapacitors allow their use for power smoothing of wind turbines, favoring the mitigation of the voltage and frequency variations at the connection point of the wind power plant.
- Regarding the use of short time-scale storage technologies, their optimal location in the wind plant and sizing have to be addressed in order to ensure their proper operation. In addition, since the C-PCS of the ESS have to interact with the power converters of wind turbines in most of the cases, the topology of the wind plant, as well as the wind turbine types and control strategies play a key role in the system operation and design.
- Other aspects related with the system stability under perturbations, like oscillation damping issues and LVRT capability, become clearly improved with energy storage support. These capabilities take on a key role from their incorporation into grid codes. Once more, energy technologies with high ramp rates are required.
- The technical feasibility of isolated and hybrid systems with high penetration rates of wind power becomes significantly improved since the predictability of wind power plants with ESS is increased. Also, a continuous power supply for the loads of such systems can be ensured.
- The predictability improvement of the output of wind power plants with an ESS not only involves technical benefits that favor the incorporation of wind power in the network, but also

economic benefits owing to penalty reductions in forecasting errors. In addition, operation costs of the power system can be reduced due to the reduced power reserve requirements of the system.

- The installation of ESS strongly depends on the economic viability of the project. In this sense, although hydrogen-based storage technologies have a great potential for long term storage applications, the main challenges for their inclusion are related to the uncertainty of their economic viability (due to high system costs and low energy efficiency) and the dependence on high hydrogen market prices.
- A proper control strategy by the system operator is necessary in order to ensure the correctness in the utilization of long term storage technologies. In addition, it is found that ESS operators should receive subsidies according to the emissions that would imply the use of conventional fuel plants for peak shaving applications, in order to make their use economically profitable.
- Nowadays, there is a tremendous effort in improving the capabilities and efficiencies of the available storage technologies, as well as reducing their capital costs. The aim of this research is to make ESS economically suitable for the use in stationary applications and, therefore, allow higher penetration ratios of renewable energies in the power system.

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